Review of the stock assessment and harvest strategy for the eastern Bering Sea snow crab

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Executive summary

This report reviews the length-based stock assessment and harvest strategy for eastern Bering Sea (EBS) snow crab. I spent the period of 16^{th}-20^{th} of June 2003 in Seattle at the Alaska Fisheries Science Center (AFSC). Most of this time was spent discussing the assessment and management strategy with Dr. Benjamin Turnock. In addition, Dr. Billy Ernst presented his work on Bering Sea snow crab, and a conference call was held with Drs. Jie Zheng and Shareef Siddeek of the Alaska Department of Fish and Game.

A) Strengths and weaknesses of the snow crab population dynamics and harvest strategy models.

In general, the stock assessment model (Turnock's draft) is consistent with previously published length-based stock assessment models. The model effectively uses the majority of the available data. Unfortunately, there is no reliable external information for several of the critical biological parameters of the model (e.g. natural mortality and growth). Therefore, the values of these parameters have to be assumed, based on limited data, other species, and/or estimated within the stock assessment model. The stock assessment model has a poor fit to some of the CW frequency data and the early female survey biomass. Additional modeling and/or data collection is required before reliable results from the stock assessment modeling will be available.

The new harvest strategy is complex and based on several different definitions of abundance and harvest rates. The harvest strategy can be data-based, using assumptions about the values of F_{MSY} and $B_{MSY,}$ or mode-based, using estimates from the stock assessment model. Both approaches have problems. The data-based approach assumes catchability is 1, which, from the available data, is most likely to be an over estimate. It also assumes F_{MSY} is equal to M, which is unknown and assumed to equal 0.3. Finally, B_{MSY} is assumed to be equal to the average total mature biomass (males and females) from the surveys of 1983 to 1997, and it is unknown how this average biomass is relates to B_{MSY}. The model-based approach contains highly uncertain estimates because of the lack of knowledge of the biological parameters. Additional modeling and/or data collection are required before reliable estimates of GHLs will be available.

B) Recommendations for alternative model configurations or formulations

I suggest several modifications to the length-based stock assessment model: (this sentence might not be necessary because of the previous sentence)

- The catch equation should be used to model the pot and trawl fisheries simultaneously.

- A catchability parameter should be added to avoid limitations on the survey selectivity curve.
- The distribution of recruits over the CW size classes should be reparameterized.
- The model should be fit to CW data by maturity rather than using the average proportion mature.
- A different formulation for the growth transition should be used to avoid negative growth.
- A method should be developed to include the northern part of the survey into the stock assessment.
- The stock assessment model is complex and uses many different data sets and alternative less complex models should be considered for exploratory analysis of the data.

C) Suggested research priorities to improve the stock assessment.

The research on EBS snow crab needs to be directed towards solving the current problems with the assessment and management of this stock. Progress should be made in the next few years with a concerted effort and appropriately planned research that includes both modeling and data collection. Results using the new data and assumptions should allow for a better understanding of the fishery, with the possibility of higher yields and a sustainable resource.

The three most important areas of research that need to be carried out immediately are: (1) catchability of the survey; (2) natural mortality; and (3) effective spawning biomass. I suggest that the commercial catch data should be compared with the ice shelf and survey (for periods they overlap) to determine the portion of the population that is exploited. In addition, either a trawl survey at the time of the fishery or a tagging study should be performed, whichever is most practical and cost effective, keeping in mind that tagging may also provide information on mating migrations and M. The terminal molt hypothesis should be solidified and the shell age classification system should be verified as well. Research should be carried out to determine if new males mate at least once before capture and the effective spawning biomass.

Background

The eastern Bering Sea (EBS) snow crab stock was classified as overfished in 1999 by the National Marine Fisheries Service (NMFS) due to low mature biomass estimated by the NMFS survey (Zheng et al. 2002). The Magnuson-Stevens Fishery Conservation and Management Act requires that a rebuilding plan be developed for an overfished stock. In response, the Alaska Board of Fisheries adopted an interim harvest strategy for the EBS snow crab fishery (Zheng et al. 2002). The harvest strategy has a variable mature harvest rate based on total mature biomass (see Figure 7 of Zheng et al. 2002) and a cap of 50% of the exploitable legal males. The abundance of exploitable legal males was defined as 100% new shell males and 25% old shell males ≥ 102 mm carapace width (CW). The estimates of abundance were taken from the trawl survey with catchability assumed equal to 1 (Zheng et al. 2002). Previous to the rebuilding plan, the guideline harvest level (GHL) of retained crab was set at 58% of the number of male crab ≥ 102 mm CW estimated from the survey (Zheng et al. 2002). The legal size is 78 mm, however crab processors prefer a minimum size of 102 mm (Zheng et al. 2002).

The interim harvest strategy was not fully investigated before implementation. Zheng et al. (2002) used several analyses, including simulation analysis, to develop alternative harvest strategies and compare their performance against the interim harvest strategy. From their analyses, Zheng et al. (2002) recommended using a new harvest strategy comprising four components: (1) a threshold of 25% of B_{MSY}, calculated as the average total mature biomass (males and females) from the surveys for the years 1983 to 1997 (Turnock's draft), below which the fishery is not opened; (2) a 58% harvest rate on exploitable legal males, which are defined as 100% new shell and a percentage of old shell males ≥ 102 mm CW, where old shell selectivity is determined by the historical fishery selectivity; (3) exploitation rate caps on mature male biomass to be: (a) 75% of the fishing mortality that produces maximum sustainable yield (F_{MSY}, currently equal to the assumed natural mortality of 0.3) when total mature biomass is ≥ B_{MSY}; (b) one third of F_{MSY} when total mature biomass is equal to the threshold; and (c) a linear function of total mature biomass when total mature biomass is greater than the threshold and less than B_{MSY}; and (4) a minimum guideline harvest level (GHL) of 25 million pounds in order to open the fishery.

As with the interim harvest strategy, Zheng et al. (2002) recommend that area swept trawl survey estimates of abundance be used to calculate the GHLs for 2003. They also recommended that a length-based assessment model be tested and considered for determining GHLs in later years. The survey estimates of abundance have considerable uncertainty and are probably biased because catchability is likely to be less than one. A stock assessment model allows the inclusion of additional information that may improve the estimates of abundance. For example, a length-based stock assessment model can include information about the relative proportion of individuals by length, sex, maturity, or shell status. The assessment model can also include information from the fishery including total catch and the relative proportion of individuals by length, sex, maturity, or shell status in the catch. This additional information, along with the understanding of the population dynamics as represented by the population dynamics model, may allow for improved estimates of abundance. For example, the stock assessment model may provide estimates of catchability for the trawl survey. The stock assessment model may also provide better estimates of B_{MSY} and F_{MSY} that are also used in the harvest strategy for calculating GHLs.

A length -based (carapace width) stock assessment model has been developed for the EBS snow crab (Turnock's draft). This model includes structure to represent males and females, mature and immature individuals, old and new shell individuals, and 5 mm CW class intervals. The data used in the model includes retained catch from the pot fishery, discarded catch from the pot fishery, trawl fishery bycatch, total survey biomass estimates, survey size frequencies by sex, shell condition, retained male size frequencies by shell condition for the pot fishery, discarded male and female size frequencies for the pot fishery by shell condition, and trawl fishery bycatch size frequencies by sex. The model has been used to estimate the time series of abundance of snow crabs in the EBS by sex, shell condition, maturity and size. The model has also been used to estimate F_{MSY}, B_{MSY} and the GHL for 2003.

Description of review activities

I spent the period of 16th-20th of June in Seattle at the Alaska Fisheries Science Center. Most of this time was spent discussing the assessment and management strategy with Dr. Benjamin Turnock. In addition, Dr. Billy Ernst presented his work on Bering Sea snow crab and a conference call was held with Drs. Jie Zheng and Shareef Siddeek of the Alaska Department of Fish and Game. Several background documents were provided and they are listed in appendix A. The AD Model Builder (ADMB) code and data files were also supplied.

Background documents

Several background documents were provided before the review (see appendix A for additional details). These documents were read prior to the meeting in Seattle and a list of clarification questions was prepared for Dr. Turnock.

1) "Stock assessment of eastern Bering Sea snow crab" by Benjamin Turnock. This document is an initial draft of the eastern Bering Sea snow crab assessment. It describes the fishery and historical management, the stock assessment model, the data used in the assessment, biological parameters, and initial results.
2) "Overview of recommended harvest strategy for snow crabs in the eastern Bering Sea" by Jie Zheng et al. (2002). This document describes a simulation analysis used to evaluate different harvest strategies for snow crabs in the eastern Bering Sea. The authors recommended a new harvest strategy, which is currently being used.
3) "Some reference points used in US and Canadian crab fisheries and a comparison of a referential system estimated using a length-based method for snow crab (*Chionoecetes opilio*) and Dungeness crab (*Cancer magister*)" by Shareef Siddeek et al. This draft document describes reference points for crab stocks and calculates them under different assumptions. They conclude that a precautionary approach to reference points is required due to the lack of reliable estimates for several life history parameters.

4) "Report to industry on the 2002 eastern Bering Sea crab survey" by B. Stevens et al. (2002). This report describes the survey methodology and results for the 2002 eastern Bering Sea survey. One important result for the snow crab population is that the relatively large abundance of new shell males seen in 2000 and 2001 were not seen in the 2002 survey as either new shell or old shell males.

Several other published and draft papers and reports not initially supplied for the review were also referred to for additional information. These are cited in the reference section.

Presentation by Dr. Billy Ernst
On Tuesday the 17th of June, 2003, Dr. Billy Ernst, a post doctoral researcher at the University of Washington, presented his work on EBS snow crab. He presented five areas of research:

1) Spatial structure of the population. There is an ontogenetic movement towards deeper warmer water. There is also a north-western shift in the population over time.
2) Female size-at-maturity. Size at maturity is smaller in the north.
3) Sex ratio. The sex ratio favors males in the south and females in the north. Calculation of the sex ratio based on spatially stratified sex ratios weighted by female abundance produces different results than the simple aggregated ratio. This indicates that spatial distribution of sex ratios is important for calculating effective spawning biomass.
4) Catch distribution. The catch distribution is centered further off shore than the population distribution at the time of the survey. Harvest rates in many areas (between 100-200 m isobaths) are higher than 1. This indicates that either the area-swept survey estimates are underestimates or there is movement of males between the time of the survey and when the fishery occurs.
5) Estimation of natural mortality for the mature female population. Natural mortality was estimated using survey estimates of mature female abundance by shell condition. The estimates are sensitive to the assumptions about the age of old shell individuals.

Conference call with Drs. Jie Zheng and Shareef Siddeek of the Alaska Department of Fish and Game
On Wednesday the 18th of June, 2003, Dr. Turnock and I held a conference call with Drs. Jie Zheng and Shareef Siddeek of the Alaska Department of Fish and Game. Drs. Zheng and Siddeek described what they considered the important factors of the eastern Bering Sea snow crab stock assessment and management. This also gave me the opportunity to ask several questions to clarify aspects of the stock assessment and harvest strategy.

Drs. Zheng and Siddeek brought up several concerns about the stock assessment and management strategy. The stock assessment model is complex and sensitive to assumptions. They suggested that simpler models might also be useful such as a model that starts at an older (larger?) CW and includes catch size frequency assuming no error. They still have concerns regarding the terminal molt hypothesis because it implies unrealistically high natural mortality rates to be able to fit the survey shell condition data.

They note that the natural mortality is uncertain and may change over time causing the stock assessment to overestimate the low abundances. The stock recruitment relationship and spawning biomass are also uncertain and these are important for the harvest strategy calculations. They also are interested in seeing retrospective analyses and the inclusion of the survey data north of 61.9 degrees north.

Development of an improved estimator for mature female natural mortality from the survey data
On the morning of Thursday the 19th of June, 2003, Dr. Ernst and I modified the analysis presented by Dr. Ernst to estimate natural mortality for mature females from the trawl survey data (see Appendix C).

Review of the model equations
On the afternoon of Thursday the 19th Dr. Turnock and I went through the equations in the appendix of the draft stock assessment document. The equations were only an initial draft of those used in the stock assessment model. They were incomplete and needed several corrections. The goal of this activity was to make sure that there was an accurate description of the equations used in the model and to identify any corrections or improvements required for the equations used in the model. The appendix was considerably modified to accurately reflect the equations used in the model and to ensure its completeness. Only minor corrections and improvements were made to the equations used in the model. For example, the catch equation was used to model the pot and trawl fisheries simultaneously, a catchability parameter was added to avoid limitations on the survey selectivity curve, the distribution of recruits over the CW size classes was reparameterized, and the model was fit to CW data by maturity rather than using the average proportion mature.

Development of a Microsoft Excel version of the assessment model
On the morning of Friday the 20th of June, 2003,Dr. Turnock and I constructed a replicate of the stock assessment model using Microsoft Excel. I initiated the construction of this model prior to the review, but due to the incompleteness of the equations I was unable to complete the model. Unfortunately, we did not have time during the review to complete the model. The main objective of this project was to validate the ADMB code. The population dynamics component of the model was only completed for the male population and predicted catch-at-size by the pot fishery. The results indicated that there were no serious problems with this component of the ADMB code.

Summary of findings

In general, the stock assessment model (Turnock's draft) is consistent with previously published length-based stock assessment models (e.g. Zheng et al. 1995; Punt and Kenedy 1997; Zheng et al. 1998; Maunder 1999; Starr et al. 1999; Fu and Quinn 2000). The model effectively uses the majority of the available data (it does not use the survey catchability bag experiment data, the shell aging data, or CPUE data). Unfortunately, there is no reliable external information for several of the critical biological parameters of the model (e.g., natural mortality and growth). Therefore, the values of these parameters have to be assumed, based on limited data, other species, and/or estimated within the stock assessment model. The stock assessment model has a poor fit to some of the CW frequency data and the early female survey biomass. Additional modeling and/or data collection is required before reliable results from the stock assessment modeling will be available.

The new harvest strategy (Zheng et al. 2002) is complex and based on several different definitions of abundance and harvest rates. The harvest strategy can be data-based using assumptions about the values of F_{MSY} and B_{MSY}, or model-based using estimates from the stock assessment model. Both approaches have problems. The data-based approach assumes catchability is 1, which, from the available data, is most likely to be an overestimate. It also assumes F_{MSY} is equal to M, which is unknown and assumed to equal 0.3. Finally, B_{MSY} is assumed to be equal to the average total mature biomass (males and females) from the surveys for the years 1983 to 1997 (Turnock's draft), and it is unknown how this average biomass is related to B_{MSY}. The estimates from the stock assessment model are highly uncertain because of the lack of knowledge of biological parameters. Additional modeling and/or data collection is required before reliable estimates of GHLs will be available.

Stock assessment

The stock assessment model relies on several uncertain biological parameters and assumptions. For example, natural mortality and growth are unknown for the EBS snow crab (Turnock's draft). There has also been controversy over the terminal molt to maturity for males and recruitment is highly variable for EBS snow crab while no stock-recruitment relationship is apparent (Zheng et al. 2002). However, as a precautionary measure, stock-recruitment relationships are usually included when developing harvest strategies. Snow crab have a complex reproductive strategy and fishing mortality is mainly on males, so if spawning biomass is to be used in the management of this stock, the appropriate calculation of spawning biomass needs to be determined.

Biological parameters

<u>Natural Mortality</u>

Natural mortality (M) is one of the most important parameters in fisheries stock assessment. It can influence both the assessment of the status of the stock and estimates of management quantities. For example, natural mortality can influence the estimates of maximum sustainable yield (MSY) and the biomass that produces MSY (B_{MSY}). In addition, the snow crab management strategy uses M as a proxy for the fishing mortality that produces MSY (F_{MSY}). Therefore, it is important that reliable estimates of M are available.

The current snow crab assessment model includes several aspects of the snow crabs life history. The model divides the population into mature and immature, males and females, and old and new shell. It also models the CW of the individuals in 5mm size class bins. It is possible, and probably likely, that these different categories and different sizes within each category have different rates of natural mortality. Small (Livingston 1989; Otto

1998) and soft shell individuals may be more vulnerable to predators, maturity may inflict extra energy costs, soft shell individuals may be more vulnerable to predation, and old shell individuals may experience senescence. In addition, the rates of M may change over time as the environment or other factors change.

It is impossible to include all the possible variation in M into a stock assessment model. The goal of modeling is to include enough information about M that useful management advice can be provided. Unfortunately, there is very little information about M for snow crab. The two main sources of information available for M are the survey data and the radiometric aging data.

Survey data is available for several years. The data include estimated abundance of snow crabs by sex, maturity, shell age, and size. Dr Billy Ernst presented an analysis of the female mature survey data developed to estimate M. Females are assumed to be subjected to little fishing mortality and the decline of a cohorts abundance from one year to the next is mostly due to M. Unfortunately, the survey individuals are not aged and cohorts cannot be directly counted. However, information on shell age can be used as a proxy for age. In Dr Ernst's analysis, he assumed that the difference between new shell (sh-2) and the first old shell category (sh-3) is one year and then looked at several different possible ages between sh-3 and the combined older old shell individuals (sh-4+). Dr Ernst estimated natural mortality equal to 0.422 when assuming 3 years between sh-3 and sh-4+. He also estimated that natural mortality was higher (about 0.7) before and lower (about 0.3) after 1983. Assessments of other crab species have considered different levels of natural mortality over time (e.g., Zheng et al. 1995).

The uncertainty of the age of sh-4+ might cause bias in the estimates of natural mortality. A less biased analysis is to avoid making any assumptions about the age of old shell individuals by modeling only old and new individuals. This analysis was carried out and produced estimates of 0.736 for female natural mortality and 1.472 for male total mortality for individuals $\geq$ 102 mm CW (see appendix C for details of the model).

These estimates are considered higher than expected. Possible explanations for bias in the estimates of natural mortality are non-terminal molt at maturity, misclassification of old and new shell individuals, higher fishing related mortality than assumed, and different catchability to the survey for old and new shell individuals. There is also inconsistency in the trawl survey data with large numbers of new shell mature females in 1979 and 1980 not appearing in the older shell categories in following years (Figure 1). There are also large numbers of old shell females in 1989, 1990, and 1991, which do not correspond to the assumed intervals between the different shell conditions. Inclusion of uncertainty in the survey estimates of each category may be important for these calculations. Terminal molt is accepted for females and only a small amount of controversy for males exists due to the terminal molt assumption producing high estimates of natural mortality. Changes in the classification of old and new shell individuals are possible and there is already evidence that the classification has differed between the surveys and the commercial catch data (Jack Turnock personal communication). The stock assessment model assumes that 80% of old shell males in the catch are classified as new shell. Dr Ernst showed that the spatial distribution of old and new shell individuals differs somewhat and this may allow for a different catchability of these two categories.

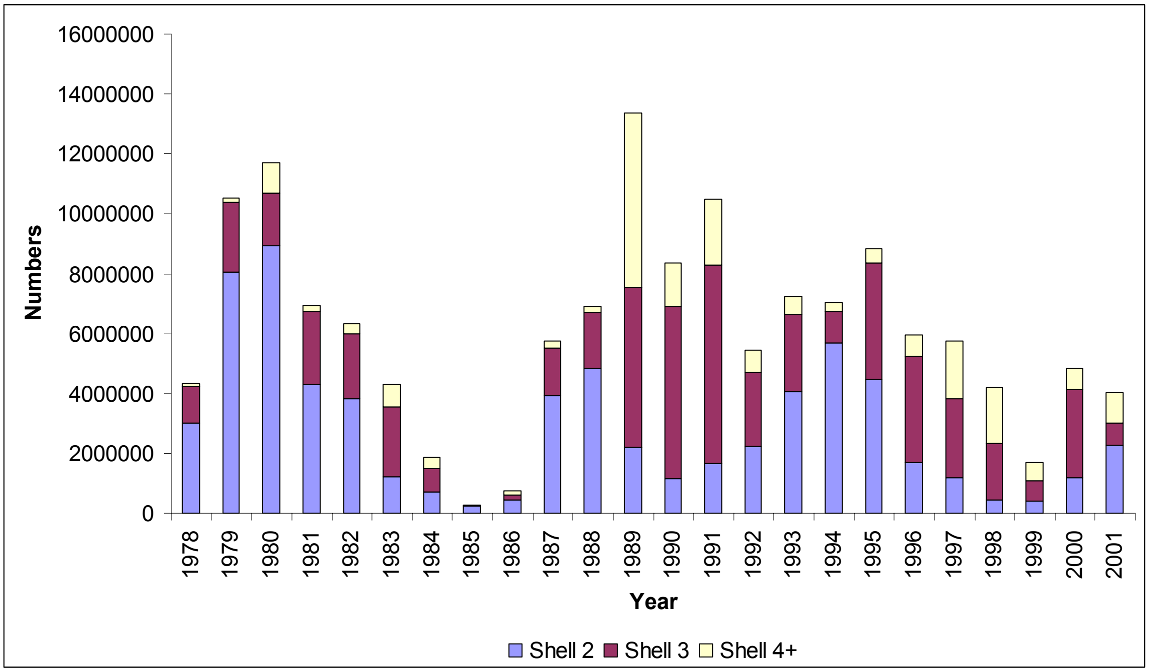

Figure 1. Female numbers by shell condition over time from the trawl survey.

There are a few samples of radiometric shell aging of male snow crab shells (Figure 2). This information does not give the age of the individual, but only the age of the shell. Given the assumption of terminal molt to maturity, it may be possible to use this information to determine the longevity of snow crab. The longevity can then be used to determine the rate of natural mortality or total mortality in the case of males. The ages range from newly formed to about 7 years. The maximum age of 7 years found in this sample may indicate the longevity of snow crab males. It should be remembered that this is the age of the shell since the last molt, not of the individual (the individuals could be several years older). The samples for the oldest shell category (sh-5) were a sub-sample taken from a large sample of sh-5 in an effort to find the oldest individuals (Lobo Orensanz, personal communication). Because it is not known what portion of the population that these individuals represent, it is difficult to associate longevity with natural mortality. Also, only males were aged and they would have experienced significant fishing mortality. At an estimate of M = 0.736, only about one percent of the population (terminal molt individuals) would be 7 years old or older. It is unknown if finding two seven year old shells in the sample is consistent with M = 0.736 or a higher value for Z when fishing mortality is considered.

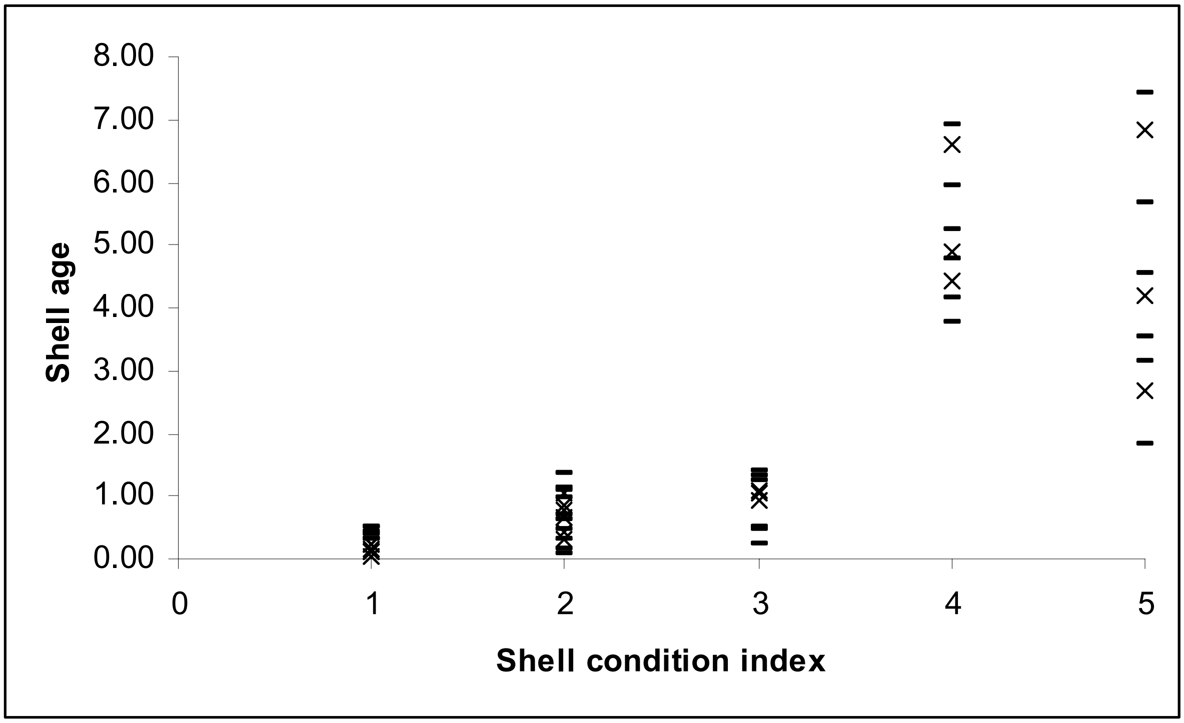

Figure 2. Shell age for individuals categorized into shell condition. x = age and - = upper and lower 95% confidence intervals of the age estimate. Data supplied by Dr. Ernst.

Initial runs of the stock assessment model carried out by Dr. Turnock indicated that the likelihood increased as M on mature males was increased up to 0.5, the highest level considered. Zheng et al. (1995) estimated M of above 1 for the early 1980s and around 0.3 for the other time periods for red king crab. Fu and Quinn (2000) estimated that M increased in the 1980s for pink shrimp in Kachemak Bay. It is not certain if these estimates are an artifact of the modeling or actually represent the annual variability in M.

<u>Growth</u>

Growth is another important biological process that is required to perform stock assessment and provide management advice. There is very little information on growth for EBS snow crab (Turnock's draft). Growth was estimated from 14 male crabs collected in March 2003 that had molted soon after capture. Female growth was assumed to be equal to male growth, but growth may be different between the sexes (note that size at terminal molt is different). The length-based stock assessment model uses a growth transition matrix to move individuals among size classes as they grow. Unlike catch-at-age models, catch-at-length models (including length-based models) require estimates of variation in growth as well as mean growth. The growth variance parameters were arbitrarily fixed to give a CV of about 0.1. Unfortunately, the estimates of growth for the snow crab assessment model are highly uncertain. Several catch-at-length models estimate growth inside the stock assessment model (e.g., Fournier et al. 1998; Hampton and Fournier 2001; Maunder and Watters 2003). However, there is often insufficient information in the data about growth and some aspects of growth need to be fixed (for example Maunder and Harley (2002) fixed the variation in growth for bigeye tuna in the eastern Pacific Ocean based on otolith data from the western-central Pacific Ocean).

The fishery focuses on new shell males ≥ 102 mm CW. These individuals are mostly terminal molt and therefore do not grow (assuming the terminal molt hypothesis is correct). In this case, growth may not effect yield calculations. However, because the length frequency distributions for different categories (e.g., male-female, new shell-old shell, mature-immature) are used to provide information for the length-based stock assessment model, the values of the growth equation and the variation in growth may be important for the model because the ratios of abundance of different categories can provide information (c.f. the change in ratio method). Sensitivity analysis should be carried out to see if growth is important.

A cursory examination of the survey data suggests that there may be density dependent growth occurring within large cohorts. Comeau et al. (1991) also found evidence of density dependence in the molt to the mature males phase. This may have an influence on yields if maturity and terminal molt subsequently occur at smaller sizes. Lower growth may also cause problems with fits to the CW data.

Model assumptions

<u>Growth</u>

The model assumes that the variation in growth is normally distributed around the mean, which allows for negative growth. The implementation also allows for all individuals that become smaller than the smallest size group to be accumulated in the smallest size group. Other formulations for growth should be considered. For example, Maunder (1999) used a lognormal distribution and Zheng et al. (1995) used the gamma distribution (see Sullivan 1998; Sullivan et al. 1990; and Ernst 2002 for more details on the use of the gamma function).

<u>Stock recruitment relationship</u>

No stock recruitment relationship is assumed in the stock assessment model. This is probably a reasonable assumption because the model is able to estimate recruitment for every year without the use of a stock recruitment relationship. A stock recruitment relationship would not provide any substantial information to the assessment. However, inclusion of a stock recruitment relationship is needed for the harvest strategy estimation (see below).

<u>Recruitment sex ratio</u>

The model assumes that recruits have a sex ratio that can differ from one based on the size of a penalty that is applied in the estimation procedure. This might be possible due to the lower growth rate of females. However, comparison of the sex ratios by size from the survey suggests that the lowest size groups have a sex ratio that is approximately equal to one. It should be noted that the sex ratio by size changes substantially from year to year. The simulations used by Siddeek et al. (draft) suggest that some management parameters are sensitive to the recruitment sex ratio. Therefore, sensitivity analyses should be carried out for the recruitment sex ratio with a sex ratio of one (a large penalty used in the stock assessment model) considered for the base case assessment.

Terminal molt

There is still a small amount of uncertainty about the terminal molt due to the unrealistically high level of natural mortality that is needed to fit the survey data when the terminal molt assumption is used. Recent studies have found that morphologically mature males show no evidence of a new shell forming under the existing shell and hormone effects are consistent with terminal molt (Jack Turnock, personal communication). However, the non-terminal molt hypothesis is more precautionary in respect to harvest levels (Zheng et al. 2002).

Multinomial likelihood for proportion data

The multinomial likelihood is used for the proportion data. The multinomial likelihood or likelihoods based on the multinomial are the most commonly used for catch-at-age or catch-at-length data. However, the actual sample size is often much larger than the effective sample size because the sampling does not correspond to the assumptions of the multinomial distribution (e.g., the samples are not independent) and the stock assessment model does not include all the process error that may affect the proportions. Unfortunately, a reasonable solution to the calculation of the effective sample size is not available. McAlister and Ianelli (1997) present a method using iterative re-weighting, but Maunder and Harley (2003) show that this method may not be appropriate because it produces unreasonably narrow confidence intervals. The sample size can, in some cases, have a large influence on the stock assessment results (Maunder and Harley 2003). Therefore, a sensitivity analysis should be carried out to determine the influence of the sample size.

Catchability for the trawl survey

The logistic selectivity curve for the trawl survey is also used to represent catchability, which may restrict the shape of the selectivity curve. For example, if the selectivity is 0.5, the selectivity is restricted to be a concave curve. In this case, the selectivity is either compromised or the catchability is increased to allow a non concave part to the selectivity curve. Adding the catchability coefficient, allows more flexibility in the selectivity curve. When implemented, this greatly increased the fit to the data as measured by the total likelihood.

Pulse fishery

The model assumes that the fishery occurs as a single pulse at the mid point of the fishery. In fact the fishery is spread over a number of months, and the length of the fishery period has changed over time. It is unknown how much effect this would have on the results, but this method is used frequently for applications where the fishery extends over the whole year.

Time specific selectivity

The model allows the selectivity of the fishery to change over time. This is implemented by allowing the 50% selectivity parameter to change over time, but is penalized to be somewhat consistent from year to year. This is a reasonable assumption, but it is uncertain what the penalty should be. Sensitivity analysis to this penalty should be carried out.

<u>Constant survey selectivity and catchability</u>
The assessment model assumes that catchability and selectivity of the survey have been constant over the whole timeframe of the analysis. However, the survey data indicate that there may have been a change in selectivity or a change in catchability (perhaps different for old and new shell) between the start and end of the time.

Data used in assessment model
The data used in the model includes retained catch from the pot fishery, discarded catch from the pot fishery, trawl fishery bycatch, total survey biomass estimates, survey size frequencies by sex, shell condition, retained male size frequencies by shell condition for the pot fishery, discarded male and female size frequencies for the pot fishery by shell condition, and trawl fishery bycatch size frequencies by sex.

<u>CPUE data</u>
CPUE data is not used in the stock assessment. The CPUE data shows a much more stable trend over time than the survey data (Stevens et al. 2002), probably due to a contraction of the area occupied by stock in years of low abundance and the ability of the fishery to target the high abundance areas. Therefore, CPUE data would not provide information on abundance. However, it may be possible to do depletion analysis within a year due to the high exploitation rates on mature males. It might also be possible to provide an index of abundance from the trawl bycatch data. However, the sample size may limit its usefulness.

<u>Survey biomass</u>
The model fits to total male and total female survey estimates of biomass separately. However, because the proportion data is separated into male and female, the model is using the sex data twice.

The 1985 and 1986 survey biomass estimates are very low and the model is unable to fit them. Reasons for this discrepancy should be investigated.

<u>Survey proportion data</u>
Currently the stock assessment separates the mature and immature individuals based on the average proportion mature by CW. However, the proportion mature may change over time because as the recruiting cohorts fluctuate more or less immature individuals will be entering the population. The survey data should be separated into mature and immature using the measurements from the survey (if available) and the model predictions fit to these measurements.

Management strategies
The current harvest strategy is data-based and uses the survey abundance estimates to develop the GHL. A similar strategy based on the estimates from the stock assessment

model has been proposed for producing future GHLs (Zheng et al. 2002). Both approaches have problems that are discussed below.

The GHL previous to 2000 was based on 58% of the number of male crab ≥102 mm CW estimated from the survey. However, it is not known how the value of 58% was determined. The F0.1 level for snow crab using a non-terminal molt model is 0.57 (Zheng et al. 2002) and the 58% may be based on similar calculations. Harvest strategies should not be developed based on 58%, but on appropriate values from current analyses.

The harvest strategy is based on several different definitions of biomass. The overfishing threshold is based on average total mature biomass (males and females), the harvest rate is based on exploitable male abundance, and the exploitation cap is based on mature male biomass. There should be good reasons for using different definitions of biomass, and if so, they should be given in the assessment document.

There is an inconsistency between the definitions of fishing mortalities and the use of exploitation rates. For example, the harvest strategy cap is based on 0.75% F_{MSY}, but applied as an exploitation rate. Using the equation U = 1-exp(-F) (assuming a pulse fishery) U = 1 - exp(-0.75 x 0.3) = 0.201, which differs from 0.75 x 0.3 = 0.225.

The current fishery targets males ≥ 102 mm CW and may have a high exploitation rate. Part of the population matures and has a terminal molt < 102 mm CW. This could put a large genetic pressure on the stock towards smaller size at maturity. If smaller mature males are not experiencing fishing induced mortality and the size at maturity is genetically determined, it is possible that the fishery may be forcing the stock towards a smaller age at maturity. This could reduce the long-term yields.

Data based harvest strategy
There are several problems with the data-based harvest strategy including assumptions that catchability = 1, F_{MSY} = M = 0.3, and B_{MSY} = the average total mature biomass (males and females) from the surveys for the years 1983 to 1997.

<u>Survey catchability = 1</u>
It is fairly certain that the catchability of the survey is less than 1, at least for some years. In some years the catch is close to if not greater than the estimated abundance of exploitable individuals. In addition, if the survey estimates of the biomass in the areas of the fishery are used, the survey catchability has to very be small. In this case, if the harvest rule is appropriate, the GHLs calculated will be lower than desired, which would mean loss of catch.

Initial runs of the stock assessment model estimate that the catchability of the survey is substantially less than one, indicating that substantially higher GHLs may be possible. In addition, spatial distribution of the exploitable stock at the time of the survey does not correspond with the commercial fishery. The presentation by Dr. Ernst showed that survey abundance of exploitable individuals was centered closer to the coast than the fishery. This means either the individuals migrate between when the fishery occurs or that the fishery is only occurring on a portion of the population and that the survey catchability may even be lower than that estimated by the model. It is possible that the fishery, which occurs in the winter, is constrained to the deeper regions due to the ice shelf, while the survey, which is carried out in the summer, is not.

F_{MSY} = M = 0.3

The exploitation rate has a cap based on the fishing mortality rate that produces maximum sustainable yield (F_{MSY}). The cap is 75% of F_{MSY}. Because estimates of F_{MSY} are not available, the general rule $F_{MSY} = M$ is applied. In this case M = 0.3. Unfortunately, M is highly uncertain making the mortality cap is uncertain also. Under the terminal molt hypothesis, the survey data suggests a higher level of natural mortality and would imply a substantially higher mortality cap.

B_{MSY} = the average biomass from the survey over the period 1983 and 1997

B_{MSY} is calculated as the average total mature biomass (males and females) from the surveys for the years 1983 to 1997 (Turnock's draft). Because the fishery was controlled during this period based on a harvest level of 58% of the number of male crab ≥102 mm CW, it is not known how this biomass level is related to B_{MSY}. If 58% is close to the real F_{MSY} (it is actually higher (60-100%) because the catch is generally higher than the GHL (Turnock's draft)), then this average may be close to B_{MSY}, but because the level of F_{MSY} is unknown, it is unknown how this average relates to B_{MSY}. If the survey catchability is substantially less than one, then previous harvest levels may have been less than F_{MSY} causing the biomass to be larger than B_{MSY}.

Model based harvest strategy

The estimates from the stock assessment model are highly uncertain because of the lack of knowledge of the biological parameters. There is little information on the natural mortality, growth, stock-recruitment relationship, and how to define the spawning biomass. All of these are important for estimating the parameters used in the harvest strategy (F_{MSY}, B_{MSY} and current abundance). They also influence how the 58% harvest rate relates to the optimal level of harvest (see also the concerns raised in the discussion of the stock assessment model reported in the previous sections). Additional modeling and/or data collection is required before reliable estimates of GHLs will be available from the stock assessment model.

A stock assessment model is a method to combine all available data and improve estimates of quantities used in management. The abundance estimates from the survey include uncertainty. The model is expected to reduce this uncertainty and any bias. However, Dr. Zheng has pointed out that the stock assessment model consistently estimates lower abundance when the survey abundance estimates are high and higher abundance when the survey abundance estimates are low (see Figures 7 and 8 of Turnock's draft). This result is true when catchability is not assumed equal to one, but is in terms of relative abundance. The error assumption for the survey abundance is a set of independent lognormal likelihoods. Therefore, this trend in residuals from the model should not be expected, indicating that the stock assessment model overestimates biomass when the biomass is low. This is a concern for managing the population when using the stock assessment model. Dr. Zheng suggests that it may be due to temporal variability in natural mortality.

For a model based harvest strategy, the estimates from the stock assessment should be carried through to the calculation of the GHL. This will ensure that any sensitivity analyses performed for the stock assessment model will also be used for the calculation of GHL. It is the calculation of the GHL that is the final goal and sensitivity of the GHL to the biological parameters is more important than the sensitivity of the underlying assessment model. The GHL may not be sensitive to some of the model unknowns. Siddeek et al. (draft) show that management strategies for crabs are sensitive to several assumptions.

<u>Calculating spawning biomass</u>
The majority of the fishing mortality occurs on terminal molt males. Without the assumption of a stock recruitment relationship, the maximum yield would be achieved by harvesting all the mature males. However, to be precautionary, the spawning stock size should be considered in the analysis. Fishing only on males unbalances the sex ratio. Therefore, the biology and behavior of the species needs to be considered in determining the effective spawning biomass. This essentially involves estimating the number of successfully fertilized females each year (Siddeek et al. draft). Some considerations include how many females a male can fertilize and how much sperm a female can store. The current assessment model (Turnock's draft) calculates effective spawning biomass based on several mating ratios from 1:1 to 1:3 (3 females can be fertilized by one male). However, there is much uncertainty about the exact details needed to estimate effective spawning biomass.

Dr. Ernst's presentation showed that the center of the abundance distribution for mature females is further north than the center for the distribution of mature males, based on the survey data. This limited overlap between mature males and females might indicate an effective spawning biomass that is lower than predicted. However, there may be a mating migration that brings the males and females closer together.

One major consideration of the effective spawning biomass is that new shell males may not mate (Sainte Marie 2002). Because new shell males are the target of the fishery, they may be caught in the fishery before they get a chance to mate and this might eliminate the at-least-one-chance protective strategy that is assumed for fisheries on mature individuals. Functional mature males that are morphologically immature are assumed not to mate. However, if they are able to mate this may allow them to mate at least once before becoming vulnerable to the fishery (see Somerton 1982). The range of these individuals overlaps more with the mature females (sh-2 or primiporous females) than do morphologically mature males (Billy Ernst, personal communication).

<u>Stock recruitment relationship</u>
Siddeek et al. (draft) show that the management strategies are sensitive to the stock recruitment relationship. This sensitivity is to both the parameters of the stock recruitment relationship (i.e. the steepness parameter) and the form of the relationship

(Beverton-Holt or Ricker). Unfortunately, the EBS snow crab estimates of recruitment are so variable that there is little information about the form or parameters of the stock recruitment relationship (figure 33 of Turnock's draft). This is consistent with most other commercial species that are assessed. There is little information from other stocks of crabs that can be used for determining the form and parameters of the stock recruitment relationship. Like most species, some general assumptions have to be made.

Conclusions and Recommendations

The research on EBS snow crab needs to be directed towards solving the current problems with the assessment and management of this stock. Much progress should be achievable in the next few years if a concerted effort is made and the research is appropriately planned. The research should include both modeling and data collection. Results using the new data and assumptions should allow for a better understanding of the fishery with the possibility of higher yields, and a sustainable resource. Listed below are recommended areas for future research.

Modeling

I recommend that the current length-based stock assessment approach be continued with additional analyses carried out to help understand the model.

Repeating the calculations

It is recommended that the calculations for all assessment models be repeated to check for programming errors (Maunder and Starr 2002). Developing stock assessment models is a complicated time consuming task and often errors occur in the computer code or data used in the model. An initial model using Microsoft Excel was developed for the snow crab assessment. This was developed to validate the ADMB code and it is recommended that this model be completed and extended to include the estimation of the GHL. Other methods could be used to validate the code, however using Excel is recommended because the programming style in Excel is conceptually different from the procedural C++ language used in ADMB. This is particularly prudent if the same analyst produces both sets of code.

Simulation analysis

The stock assessment model is new and there are several uncertainties in the biological parameters. Simulation analysis should be carried out to determine how uncertainties in these parameters influence the results, particularly the estimates of GHL compared to the "real" GHL. The simulations can also be used to determine what parameters can be estimated in the model. For example, can reliable estimates of growth, variation in growth, and/or natural mortality be obtained from the stock assessment model (see Fu and Quinn 2000)? For these analyses it would be useful to see how the combined stock assessment model and management strategy performs over a long period (e.g. Punt 1993).

Sensitivity analysis

Sensitivity analysis should be carried out to determine how uncertainty in the model parameters and assumptions influences the estimates of GHLs. This can be used to indicate how large the error in the estimates of GHLs can be if the incorrect parameter values or assumptions are used. These analyses can also be used as a guide to determine which parameter values or assumptions research should focus on. For example, the GHL levels may not be sensitive to some of the parameters or assumptions. Sensitivity analysis should include M, growth, the stock-recruitment relationship, effective spawning biomass, and terminal molt.

Diagnostics

It is useful to look at diagnostics to determine how well the model is fitting the data and if any assumptions are being violated. This can help determine alternative models to run and what research or data is needed. Complex stock assessment models are very different from standard methods that applied statisticians use and diagnostics methods need to be developed for stock assessment models. Harley and Maunder (2003) give some guidelines to the type of diagnostics that should be applied to large statistical stock assessment models.

Retrospective analysis

Estimates of the most recent abundance are important because they will be used for calculating the GHL. Simulation analysis (mentioned above) is one method that can be used to investigate the ability to estimate the most recent abundance. An alternative is retrospective analysis. Retrospective analysis is based on the assumption that as you add more years of data, the historical estimates of abundance are less biased and more precisely estimated. Therefore, comparing the estimates of abundance using all the data with estimates using consecutively less years of data can help highlight biases in the analysis. Retrospective analysis should be applied to help indicate potential biases in the analysis.

Simple models

The stock assessment model is complex and uses many different data sets. Often simple models are useful to help understand the data. For example, analysts often use surplus production models. The nature of the snow crab stock and associated fishery is not suitable for surplus production modeling. However, other simple models can be applied. For example, the natural mortality model described in appendix C is a simple population dynamics model. A similar model could also be applied to terminal molt males (or those $\geq$ 102 mm CW) with the inclusion of catch in the model. It is recommended that models similar to these should be used to investigate different aspects of the full length-based stock assessment model.

Bayesian analysis

Bayesian analysis is often used to represent uncertainty in stock assessments and management advice (Punt and Hilborn 1997). However, for the current snow crab assessment, it is recommended that the stock assessment model be more fully understood before Bayesian analysis is applied. At this stage of initial development, sensitivity analysis is probably more useful and informative than Bayesian analysis.

Area specific model

The presentation of Dr. Ernst showed that there is considerable amount of spatial variability in the EBS snow crab stock and that there are temporal and ontogenetic trends. This indicates that a spatially stratified population dynamics model may be suitable for this population. However, due to the current uncertainties, it is recommended that the development of a spatially stratified statistical population dynamics model as an assessment tool be delayed until the current model is fully developed and its data needs are met. It is uncertain that a spatially stratified model would improve the management of this species. The first step might be to develop a spatially stratified simulation model to investigate the inadequacies of the current assessment model due spatial structure in the populations. The simulation model could also be used to identify areas of future data collection and research and to investigate spatial aspects of the management strategy.

Including the northern part of the survey in the assessment

A method should be developed to include the northern part of the survey into the stock assessment. There are two possible candidate methods: 1) Include a southern index for all years and a northern index for the years it is available; 2) Include a full area index for the later years and a southern index for the earlier years.

Data collection

The sample size for much of the data collected from the commercial pot and trawl fisheries (e.g., discards, CW, trawl bycatch) is small. The representative nature of this data should be investigated to make sure that the data is not substantially biased. In addition, there are several types of data that should be collected to help overcome the deficiencies in the current stock assessment model and harvest strategy.

Catchability

To investigate the mismatch between the spatial distribution of the exploitable abundance estimated by the survey and the spatial distribution of the catch, several types of studies should be carried out. A trawl survey should be carried out at the time of the fishery to determine the spatial distribution of the exploitable abundance at the time of the fishery. The extent of the ice shelf should be compared to the range of the fishery. The fishery spatial distribution in the years that had catch at the same time (or close to) the survey should be compared with the survey in the overlapping months. Individuals should be tagged during the survey to determine if they migrate to the areas of the fishery. Tagging may also provide information on mating migrations and M. These studies will determine what proportion of the population the fishery is affecting, which is related to abundance and the catchability of the survey.

The survey underbag experiment (Somerton and Otto, 1999) should be repeated with larger sample sizes and area stratification to allow for the estimation of catchability for different sections of the population. For example, are there catchability differences between males and females, or old and new shell individuals?

Dr Ernst suggested that it might be possible to use within year depletion analysis on the commercial catch and effort data to determine the local abundance and thus the catchability of the survey. This may be possible because the exploitation rate on exploited males is high.

Terminal molt

The terminal molt lab experiments (hormone experiments and the observation of second shells forming under the existing shells) should be continued and more samples taken to finally solve the terminal molt controversy.

Natural mortality

The shell aging studies should be continued. However, due to the fact that it is a time consuming procedure and that only a limited number of individuals can be aged, great care should be put into determining the sample design that will give the most beneficial information.

The high estimates of natural mortality may be due to misclassification of the shell categories. There is already evidence that the classification differs between the fishery catch and the surveys (Jack Turnock, personal communication). For example, 80% of old shell individuals caught in the fishery are assumed to be classified as new shell. Therefore, studies should be developed to determine if there are any errors in the classification or if there have been any changes over time and be combined with the aging studies to determine the relationship between shell condition, age, and timing of the survey.

Tagging terminal molt individuals may provide a method to estimate natural and/or total mortality.

Old shell individuals may move out of the survey area into deeper water. Because the fishery does not target these individuals they do not appear in any of the data. A pot survey in the area outside of the survey area may indicate the presence of additional older males. It is not sure how likely this is because the center of the abundance is not close to the edge of the survey areas, and if old males do not migrate to mate, they may not provide much to the effective spawning biomass.

Effective spawning biomass

Studies should be carried out to determine the appropriate method to determine the effective spawning biomass. In particular, research should investigate whether or not the new shell males that are targeted by the fishery get a chance to mate before they are captured and if functionally mature males that are not morphologically mature are able to successfully mate.

Harvest Strategy

At present, the calculation of the GHL is probably conservative. This is because F_{MSY} = M=0.3 (which may be low), and catchability is assumed to be one. B_{MSY} (calculated as the average biomass over the years 1983 to 1997 when the harvest strategy was probably conservative) is probably conservative also. The main pitfall is the possible spatial mismatch of males to females, particularly if the new shell mature males are caught before they get a chance to mate. Therefore, as a precautionary approach I recommend that the current harvest strategy based on the survey abundance estimates should be used until the recommended research is carried out. It should be noted that F_{MSY} is only applied to the retained individuals and there may be a substantial portion of fishing mortality that is not accounted for in the GHL calculation (e.g., discards and trawl bycatch).

The timing of the fishery should take into consideration the molting and mating periods of the snow crab. This may be particularly important when the abundance is low and the fishery is only opened for a short period. If the fishery can be carried out between the time of mating and the time of male molting, this may allow new shell males to mate once.

Other harvest strategies based on the EBS snow crab stock should be investigated. This should continue the work of Siddeek et al. (draft) and Zheng et al. (2002). Decision rules (Starr et al. 1997) and management procedures (e.g., Punt 1993) should also be considered. The analyses should not be limited to maintaining the 58% harvest rate used in the historical management of this stock. While these analyses are carried out it should be kept in mind that this fishery is conceptually different from most other fisheries because it applies a high level of harvest to mature males and it might require a unique solution. Harvest strategies based on spatial distribution of the population provides an additional possibility.

Priorities

The three most important areas of research that need to be carried out immediately are: (1) catchability of the survey; (2) natural mortality; and (3) effective spawning biomass. I suggest that the commercial catch data should be compared with the ice shelf and survey data (for periods they overlap) to determine the portion of the population that is exploited. In addition, either a trawl survey at the time of the fishery or a tagging study should be carried out, whichever is most practical and cost effective, keeping in mind that tagging may also provide information on mating migrations and M. The terminal molt hypothesis should be solidified and the shell age classification system should be verified as well. New research shall determine if new males mate at least once before capture and the effective spawning biomass.

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Appendix A: Documents supplied for the review

Turnock, B.J. Draft. Stock assessment of eastern Bering Sea snow crab

Zheng, J., Siddeek, S., Pengilly, D., and Woodby, D. 2002. Overview of recommended harvest strategy for snow crabs in the eastern Bering Sea. Alaska Department of Fish and Game Regional Information Report No. 5J02-03

Shareef Siddeek et al. Draft. Some reference points used in US and Canadian crab fisheries and a comparison of a referential system estimated using a length-based method for snow crab (*Chionoecetes opilio*) and Dungeness crab (*Cancer magister*).

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Appendix B: Statement of Work

STATEMENT OF WORK

Consulting Agreement Between The University of Miami and Dr. Mark Maunder

July 21, 2003

General

The Alaska Fisheries Science Center (AFSC) requests review of the snow crab population dynamics and harvest strategy models which are being proposed for future use in the Bering Sea snow crab (Chionoecetes opilio) assessment. The quota for snow crab will be set this fall 2003 using a model for the first time. Management has used current survey abundance to set quotas historically. At this time several alternative models exist, some of which are based on different natural mortality scenarios, survey selectivities, whether male crab have a terminal molt, and what portion of the population takes part in mating in any particular year. This review will help in the decision process as to which alternative model is most appropriate, given the current state of knowledge of Bering Sea snow crab. There is a compelling need for independent peer review.

The consultant will need to be thoroughly familiar with various subject areas involved in the stock assessment, including population dynamics, length based models, harvest strategy models for invertebrates, and the AD Model Builder programming language. The consultant will travel to Seattle, Washington to discuss the stock assessment with the lead analyst for the snow crab assessment. The report generated by the consultant should include:

a. A statement of the strengths and weaknesses of the snow crab population dynamics and harvest strategy models;
b. Recommendations for alternative model configurations or formulations.
c. Suggested research priorities to improve the stock assessment.

AFSC will provide copies of the most recent stock assessment documents and AD Model Builder code for the parameter estimation routine.

Specific

1. Read and become familiar with the relevant documents provided to the consultant;
2. Discuss the stock assessment with the lead analyst in Seattle, Washington, from June 16 to June 20, 2003;
3. No later than July 7, 2003, submit a written report[1] consisting of the findings, analysis, and conclusions, addressed to the "University of Miami Independent System for Peer Review," and sent to Dr. David Die, via email to ddie@rsmas.miami.edu, and to Mr. Manoj Shivlani, via email to mshivlani@rsmas.miami.edu.

Signed________________________

Date____________

[1] The written report will undergo an internal CIE review before it is considered final. After completion, the CIE will create a PDF version of the written report that will be submitted to NMFS and the consultant.

Appendix C:

A simple model is used to project over time the numbers in two groups: (1) new shell individuals (N_t^{new}) and (2) old shell individuals (N_t^{old}). The new shell individuals are the recruits each time period and the only process affecting the numbers is natural mortality.

$$N_{t+1}^{old} = N_t^{new} e(-M) + N_t^{old} e(-M)$$

If it is assumed that there is no error in the estimates of abundance, an analytical solution is available for the estimates of *M* for each time period (*t*).

$$M_t = -\ln\left[\frac{N_{t+1}^{old}}{\left(N_t^{new} + N_t^{old}\right)}\right]$$

The results for mature females are shown in figure C1.

However, a statistical approach might be more appropriate to estimate a single *M* for all time periods. If using a process error estimator, the predicted number of old individuals is compared to the observed number of old individuals for each year. The old and new individuals at time *t* to predict old individuals at time *t*+1 are taken from the survey data (i.e. this method assumes no error in the survey data). Only the natural mortality and the standard deviation of the likelihood function are estimated.

$$N'^{old}_{t+1} = N_t^{new} e(-M) + N_t^{old} e(-M)$$

$$-\ln L = \sum_{t=2}^{t=T}\left[\frac{\left(N'^{old}_t - N_t^{old}\right)^2}{2\sigma^2} + \ln(\sigma)\right]$$

The estimate of M for mature females is 0.73 with 95% confidence interval between 0.35 and 1.1.

Assuming observation error only, both the new and old predicted abundance are fit to the old and new abundance from the survey. The old and new individuals at time *t* used to predict old individuals at time *t*+1 are taken from the predicted abundance (i.e. this method assumes no process error). In addition to the natural mortality, the abundance of the new individuals for all except the last year and the abundance of the old individuals in the first year are estimated.

$$N_2'^{old} = N_1^{*new} e(-M) + N_1^{*old} e(-M)$$

$$N_{t+1}'^{old} = N_t^{*new} e(-M) + N_t'^{old} e(-M) \quad t > 1$$

$$-\ln L = \sum_{t=1}^{t=T-1} \left[\frac{\left(N_t^{*new} - N_t^{new}\right)^2}{2\sigma^2} + \ln(\sigma) \right] + \left[\frac{\left(N_1^{*old} - N_1^{old}\right)^2}{2\sigma^2} + \ln(\sigma) \right] + \sum_{t=2}^{t=T} \left[\frac{\left(N_t'^{old} - N_t^{old}\right)^2}{2\sigma^2} + \ln(\sigma) \right]$$

where:

N_t^{new} are the survey estimated numbers

$N_t'^{new}$ are the model predicted numbers using the model equation

N_t^{*new} are the model predicted numbers as parameters of the model

σ is the standard deviation use as a weighting factor in the likelihood function and is estimated simultaneously with the other parameters

The estimate of M for mature females is 0.74.

The same method can be repeated for the males, but the estimates will also include fishing mortality. The model could be extended to include catch for males and discards for both sexes. The estimates might be improved if the uncertainty in the survey estimates is included in the likelihood function (e.g. as a value to scale the standard deviation).

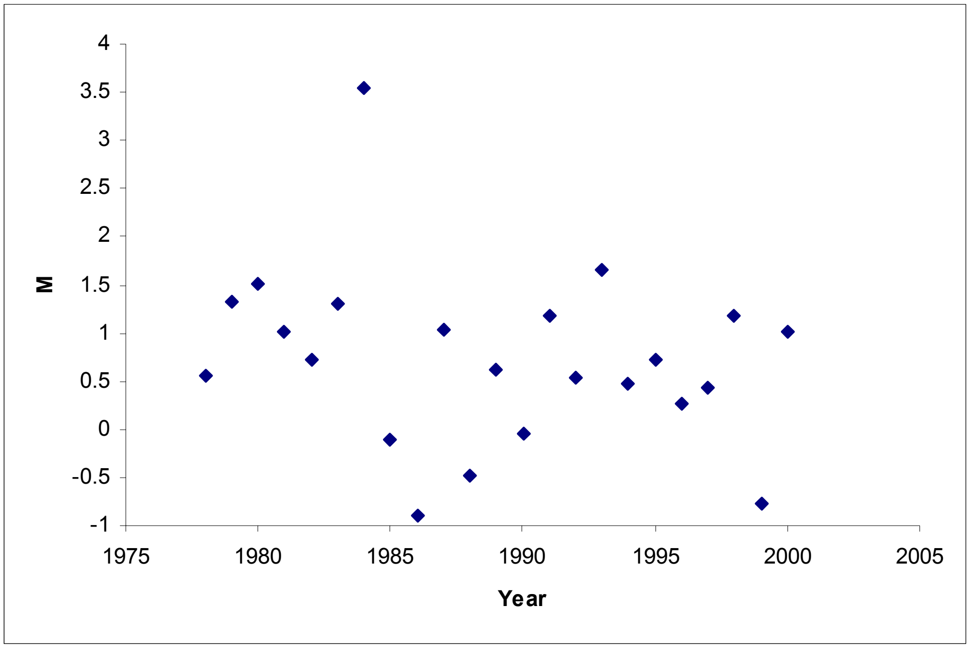

Figure C1. Annual estimates of female natural (M) mortality using the analytical formula.